

Nd-isotopic Evidence for the Origin of the Sudbury Complex by Meteoritic Impact; B. E. Faggart, A. R. Basu, Department of Geological Sciences, University of Rochester, Rochester, New York 14627; and M. Tatsumoto, U.S. Geological Survey, Box 25046, Denver, Colorado 80225.

The Sudbury geologic structure in Ontario, Canada has long attracted the interest of many generations of geologists. It is possibly scientifically the most intriguing and at the same time economically the most profitable igneous rock body on this planet. The Sudbury Complex is famous as the world's largest single supplier of nickel, although the original interest in the Sudbury ore was due to its copper content which is found in equal abundance with nickel. In addition to nickel and copper, the Sudbury rocks have produced significant amount of platinum, palladium, iridium, osmium, rhodium and ruthenium. The value of different minerals produced from Sudbury is indeed remarkable. For example, in 1981, Sudbury supplied nearly 19 per cent of the world's total nickel production, and before 1940, 80 percent of the world's nickel market was captured by Sudbury. The reserves of nickel at Sudbury is estimated sufficient for continued production into the twenty first century.

The nickel and copper are found as sulfides, along with the platinum group of metals, which are associated with a huge body of igneous rocks, collectively known as the Sudbury Igneous Complex. This complex is outlined at the surface as an elliptical ring structure, 60 km long by 27 km wide, elongated in an east-northeast direction. In general, the complex may be divided into two sections: a lower lying norite-gabbro rock body, beneath the base of which are the ore deposits of greatest economic importance, and an upper coarse-grained granophyric rock, referred to as the micropegmatite. The outer margin of the complex generally dips inward at 30° to 50°, producing a basin-like structure for the complex. The ore deposits occur around the outer and lower edge of the noritic rocks which also shoots as radial dikes into the surrounding rocks, known as the Footwall breccias. The Footwall breccias consist of rock units

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characterized by deformational and shock-metamorphic features related to the Sudbury cratering event. According to some geologists, the Footwall may be 35 to 40 km wide south of the complex. The term shock metamorphism describes changes in rocks and minerals which result from the passage of high pressure shock waves and which causes permanent structural damage to minerals and rocks. In the Sudbury Footwall rocks, microscopic and macroscopic shock-metamorphic effects are common. Another shock-metamorphic feature, known as "shatter cones" have been found around the entire Sudbury Igneous Complex for distances as much as 17 km away from it. These are conical fracture surfaces with striations that fan from an apex. These cones are up to 3 meters long in adjoining rocks around the Sudbury Complex. These breccias in the Footwall of the Sudbury Igneous Complex are some of the most intriguing rocks related to the Sudbury Structure, and in spite of many studies, the origin of these breccias remains controversial.

The close spatial association of the norite rocks with the sulfide ore deposits suggests a genetic relationship and it is generally accepted by the experts that the sulfides were introduced as immiscible sulfide liquids which segregated from the silicate magma of noritic composition in the same way as oil and water unmix.

The Sudbury Igneous Complex is also overlain by a sequence 1800 meters of heterogeneous layers of breccias, known as the Onaping Formation. The Onaping Formation consists predominantly of pyroclastic rocks, which are typically produced in terrestrial volcanoes. These rocks occur only within the Sudbury Basin where they are also intruded by the granophyres of the upper layers of the Sudbury Igneous Complex. The origin of the Onaping Formation is

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controversial, although there is general agreement among workers that the origin of this unit has an important bearing on the origin of the Sudbury structure.

There was great interest in the early sixties in the discovery and cataloguing of ancient meteorite impact scars or astroblemes on earth. It was during this period in 1964 that Dietz suggested the most provocative hypothesis that the Sudbury Structure was an astrobleme which was produced by the impact of a large meteorite. Dietz's basic thesis was that this impact was responsible for the formation of the Sudbury Breccia and the shatter cones. The impact also caused fracturing in the crust and generated magma in the deep crust which then filled the impact-crater producing the rocks of the igneous complex. Although Dietz's revolutionary idea was accepted by a few geologists, many prominent workers rejected this hypothesis. For example, in a centenary volume on Sudbury geology, commemorating the first discovery of nickel-copper ore in the Sudbury area in 1883, Dr. A. J. Naldrett, one of the editors of this volume, states on page 549 "...the author regards the impact model as a reasonable working hypothesis. It is not proven, in fact, it rests on distinctly less certain grounds than it did 15 years ago."

We have undertaken a Neodymium isotopic study of the various rock units of the Sudbury Igneous Complex along with members of the overlying Onaping Formation. The decay of Samarium 147 to Neodymium 143 with time has been used very successfully in determining the ages of lunar rocks, meteorites, as well as for terrestrial rocks. In addition to determining the ages of crystallization or time of formation of a rock body, the Samarium(Sm)-Neodymium(Nd) isotope system is also being used widely in tracing the source of origin of various types of rocks. Since the ionic radius of Nd is slightly

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larger than that of Sm, partial melting of the earth's mantle causes Nd to be somewhat more concentrated in the partial melt relative to Sm. Eventually this Nd-enriched melt crystallizes to form the earth's crust. As a result, the earth's crust has become progressively enriched in Nd compared to Sm through time and the mantle, likewise, is relatively depleted in Nd. Thus the isotopic signatures, in terms of the $^{143}\text{Nd}/^{144}\text{Nd}$ ratios, for the crust and the mantle of the earth are distinctly different. This difference is more elegantly expressed in terms of a parameter called epsilon Nd (ϵNd). Positive ϵNd means a mantle signature, whereas negative ϵNd signature means a crustal source.

We have analyzed the Sm and Nd isotopes of sixteen rocks from along two traverses, one in the north and one in the south, of the complex. Ten mineral separates from five of these rocks were also analyzed. From these analyses, we obtained an age of 1845 million years for the time of crystallization of the Sudbury Complex. This age is in excellent agreement with other workers, who determined this age using the Uranium-Lead radiometric clock. The ϵNd parameter calculated at 1845 million years before present for the different Sudbury rocks ranges from -7 to -8.8, with the majority of the rocks at around -7 to -8. These large negative ϵNd values, as explained above, are diagnostic signatures of the crust. In fact, our data suggest that all the different rock members of the Sudbury Igneous Complex, along with the different members of the overlying Onaping Formation could have formed by melting of the crustal rocks at Sudbury. In other words, we do not see any isotopic signature of a mantle component (i.e. positive ϵNd values) in these Sudbury rocks. The only viable explanation for this crustal Nd-isotopic signature is that the Sudbury Complex formed from the melting of crustal rocks by way of meteoritic impact. This

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interpretation is compatible with previous observations, such as shatter cones in the surrounding country rocks as well as shock features, including planar features within the mineral fragments of the Onaping Formation. It is also instructive to calculate the model ages of all the Sudbury rocks. Model ages are estimated as time of separation of a rock from its ultimate parent, the primitive or pristine mantle. All the Sudbury rocks define a narrow range in this model age of 2.56 ± 0.13 billion years. This model age is remarkably similar to the age of the metamorphosed volcanic and sedimentary rocks which are known to have formed the basement rocks underlying the Sudbury Structure. It is our proposition that these heterogeneous groups of rocks were impact-melted to produce the Sudbury magma(s) which underwent sulfide-rich magmatic segregations to produce the ores in the lower part of the complex.